

MULTI-PHASE HYDRODYNAMICS AND X-RAY CLUSTERS FORMATION

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We investigate the role of radiative cooling within the core of large X-ray clusters using multi-phase hydrodynamics. We developed for that purpose a spherically symmetric hydrodynamical code, coupled to a “fluid model” that describes accurately the dark matter component. Cooling is included using a self-consistent multi-phase approach, leading to “cooled gas” mass deposition throughout the flow. We simulate the collapse and the subsequent evolution of a Coma-like X-ray cluster, avoiding the well-known “cooling catastrophe”. The total mass profile of our simulated cluster is very similar to the “universal” profile proposed by Navarro, Frenk & White (1995)¹. More interestingly, we also obtain a quasi-isothermal temperature profile, which is a direct consequence of multi-phase cooling within such a potential well.

1 Introduction

Active cooling strongly regulates the evolution of the dynamically relaxed central regions of many galaxy clusters, as inferred from X-ray observations². The analysis of X-ray spectra of these regions often exhibit an excess of low-energy photons, relative to a single-temperature spectrum. Recently, high EUV brightness excess have been detected by EUVE pointed observations of the Virgo and Coma clusters³. Such observations strongly suggest the presence of cold gas at a temperature well below the average X-ray temperature of the intra cluster gas. This may be an evidence for the presence of cold parcels of gas immersed in the hot, pervasive X-ray emitting gas.

Gas cooling is a complex, unstable phenomenon. As a matter of fact, the gas is subject to the so-called *cooling instability* by which small temperature differences are amplified, leading to a clumpy structure on small scales. A long lived, tenuous hot phase can be maintained as the bulk of the mass cools down and eventually condense in cold clouds and, possibly, stars. This description of the thermal history of the gas has been investigated by numerous authors, and is known has the “multi-phase cooling flow” formalism^{4,5,6,7}.

In this paper, we intend to investigate multi-phase cooling using a fully hydrodynamical approach. We therefore proceed a step further than the usual stationary cooling flow approach. We describe the dynamical evolution of both gas and dark matter components⁸, starting from cosmologically relevant initial conditions, together with the thermodynamical evolution of the multi-phase medium, which ultimately leads to the condensation of cold clouds. We shall restrict ourselves to very high resolution, spherically symmetric simulations, since we are interested in the most central regions of X-ray clusters, where strong cooling takes place.

2 Physical and Numerical Methods

Nulsen (1986) derived the equations describing the evolution of the density distribution in a multi-phase medium. These multi-phase equations describe the flow at intermediate scales, in between microscopic scales, where atomic processes contribute to gas cooling, and macroscopic scales, relevant for the overall hydrodynamical evolution. Integrating the multi-phase equations over the density distribution, one obtains useful *modified hydrodynamical equations*. First, the continuity equation writes

$$\frac{1}{\bar{\rho}} \frac{d\bar{\rho}}{dt} + \nabla \cdot \mathbf{u} = -\beta(x, t) \quad (1)$$

where β is **the mass deposition rate** and $\bar{\rho}$ is the *mean* density in the macroscopic fluid element. Second, the energy equation writes

$$\frac{1}{P} \frac{dP}{dt} + \frac{5}{3} \nabla \cdot \mathbf{u} = \frac{2}{3} \lambda(x, t) \frac{\bar{n}^2 \Lambda(\bar{T})}{P} \quad (2)$$

where P is the gas pressure, $\Lambda(\bar{T})$ the cooling function evaluated at the *mean* temperature, and $\lambda(x, t)$ the **cooling enhancement factor**, due to the presence of an underlying density distribution. Finally, the Euler equation writes

$$\bar{\rho} \frac{d\mathbf{u}}{dt} = -\nabla P - \bar{\rho} \nabla \Phi \quad (3)$$

The usual single phase hydrodynamical equations are recovered with $\lambda = 1$ and $\beta = 0$. However, in the general multi-phase case, the functions $\beta(x, t)$ and $\lambda(x, t)$ have to be evaluated through a detailed treatment of the multi-phase distribution. This has been done so far only in the case of stationary cooling flows^{6,7}. It has been however demonstrated that, given any reasonable initial multi-phase medium, a universal high-density cooling tail rapidly develops in the mass spectrum, leading to self-similar solutions⁴. In this case, the cooling

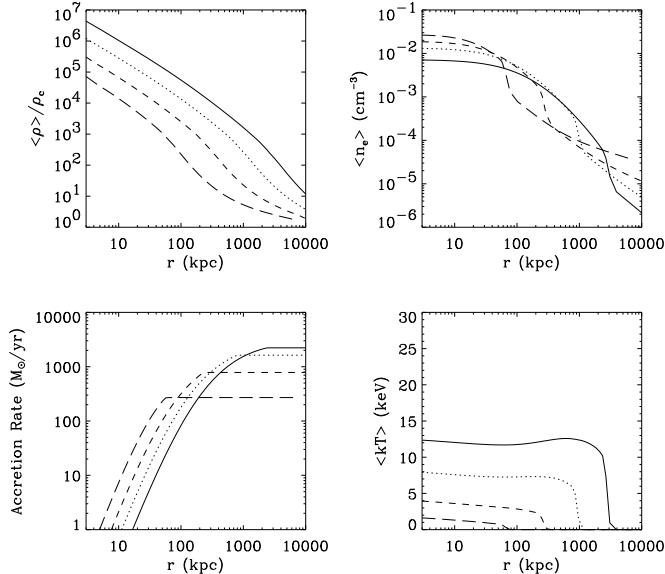


Figure 1: Simulated profiles of a Coma-like cluster: enclosed overdensity, *mean* electron density, accretion rate and *mean* gas temperature at different redshifts ($z=2.4, 1.2, 0.5, 0$). Note that the X-ray temperature is here only 70% of the *mean* temperature.

enhancement factor λ is constant all over the flow, and the mass deposition rate β is exactly proportional to the *mean* cooling rate in the macroscopic fluid element. In this paper, we neglect the short relaxation phase anterior to this asymptotic cooling flow regime. We consider only the self-similar solutions found by Nulsen (1986), parameterized by a single parameter ν . Details on our numerical treatment will be found elsewhere⁹.

3 Results and Discussion

We simulate the formation of a large X-ray cluster, similar to the Coma cluster ($M_{tot} \simeq 1 \times 10^{15}$, $\bar{T} \simeq 10^8$). We plot in figure (1) the profiles we obtained at different redshifts. The dark matter density profile is similar to the Navarro, Frenk et White (1995) universal profile, with $\rho \propto r^{-1}$ in the center. We found that only large values of the multi-phase parameter are allowed ($\nu \geq 3$), in order to avoid a cooling catastrophe. This roughly corresponds to the limiting case $\nu = +\infty$, which allows indeed a strict conservation of the gas mean

entropy, as fluid elements sink towards the center. It turns out to be the only stable case. This case corresponds to a wide temperature distribution within the intracluster medium, with small parcels of gas of arbitrary high temperature.

The X-ray emitting gas density profile show a typical core-halo structure, the core radius corresponding to the cooling radius of the cluster. Note that the central density decreases in time, due to continuous mass deposition in this strongly cooling region. This deposition process regulates the mass infall, and the central density remains at a value corresponding to $t_{cool} \simeq t_H$. The accretion rate steadily increases with radius as $\dot{M} \propto r^2$, and reaches 2000 M_\odot/yr in the outer regions, which is observed in strong cooling flow clusters. More interestingly, the mean temperature profile is nearly isothermal. This property is due, first, to the total mass profile ($\rho \propto r^{-1}$), which determines the gravitational potential, and, second, to the multi-phase model we considered ($\nu = +\infty$). We found also that the inner temperature profile is highly sensitive to the mass profile. This lead us to conclude that, within our multi-phase model, the total density profile $\rho \propto r^{-1}$ is the only one leading to an isothermal gas distribution.

The multi-phase model ($\nu = +\infty$) we use here might be considered as unrealistic, since it involves a very wide temperature distribution in the intracluster gas. We believe on the contrary that this model mimics the continuous reinjection of high entropy gas by supernovae driven winds, a very important aspect of clusters thermodynamics. A more realistic treatment of multi-phase cooling is however necessary, and we intend to include within our hydrodynamical code a complete (multi-group) treatment of the mass deposition.

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